CLAIMS

WHAT IS CLAIMED IS:

1. A device for creating a three-dimensional profile of an object or scene being imaged, the device comprising:

a light source for illuminating said object or scene with a light pattern, wherein said light pattern has a characteristic that varies across said object or scene and that includes two or more sub-patterns;

an image sensor for imaging said object or scene as illuminated with said light pattern; and

a processor for calculating a distance to a point on said object or in said scene based on a baseline distance between said light source and said camera, an angle between said camera and said baseline, and an angle at which light striking the point is emitted by said light source as determined from the characteristic of the light striking the point.

2. The device of claim 1, wherein the varying characteristic is a spatially varying wavelength, and wherein two or more sub-patterns are two or more spectra of light in the visible light spectrum such that a given wavelength corresponds to more than one projection angle.

3. The device of claim 2, wherein the processor determines the projection angle for the given wavelength via adaptive initial point calculation, wherein the processor restricts a search space for color matching in one of said sub-patterns.

4. The device of claim 1, wherein the two or more sub-patterns are two or more spectra of light in the infrared light spectrum.

5. The device of claim 1, wherein the two or more sub-patterns are two or more spectra of light in the ultraviolet light spectrum.

6. The device of claim 1, wherein the varying characteristic is a spatially varying intensity, and wherein two or more sub-patterns are three light sub-patterns corresponding to red, green and blue components of the light pattern.

7. The device of claim 6, wherein said three light sub-patterns have varying intensities, each sub-pattern having a high point and a low point.

8. The device of claim 7, wherein the high points and low points for the three sub-patterns are distributed over a spatial period of the light pattern.

9. The device of claim 1, wherein the varying characteristic is a spatially varying wavelength, and wherein the device further comprises an optical filter coupled to the light source to generate said light pattern.

10. The device of claim 9, wherein said optical filter is a linear variable wavelength filter.

11. The device of claim 1, wherein the light pattern is pre-distorted based on a pre-calibration characteristic of the image sensor.

12. The device of claim 1, further comprising a second image sensor, wherein said image sensor and said second image sensor together form a stereo pair.

13. The device of claim 1, wherein the varying characteristic is a spatially varying intensity and wherein the image sensor is monochromic and the light source generates the light pattern by sequentially emitting a plurality of light sub-patterns.

14. The device of claim 13, wherein the plurality of light sub-patterns is three light sub-patterns corresponding to red, green and blue components of the light pattern.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0037] Figures 6a and 6b illustrate one manner in which the light projection pattern can be modified to improve resolution and measurement accuracy. Figures 6a and 6b assume that the light pattern is a single rainbow projection pattern. As explained above, the light pattern contains red, green and blue (RGB) components. In one embodiment of the invention, the intensities of the RGB components in the light pattern are modulated so that the intensity of each R, G, B component varies between high and low points, i.e. from a peak to a valley, and forms multiple cycles of pattern variation. The locations of the peak-valley points for the R, G, and B sub-patterns are spread over the spatial period of the light pattern, as shown in Figure 6b. Notice that the distribution of R, G, and B does not need to be evenly spaced across the spatial period.

[0038] Because this embodiment uses a single rainbow projection pattern as the light pattern, the one-to-one correspondence between the wavelength of a light sheet in the light pattern and its projection angle still applies in this embodiment.

[0039] Referring now to Figures 7a through 7c, the light pattern from the light projector does not have to be limited to a single spectrum, where a one-to-one correspondence between a given wavelength and a given projection angle applies. Instead, the light pattern may include multiple cycles of spectra, such as multiple visible light spectra, such that a given wavelength from the light projector could be generated and transmitted in several projection directions, i.e. at several projection angles. This will be referred to as a "multiple rainbow projection" pattern, even though the spectra is not limited to the visible rainbow light spectrum. Because a given wavelength will no longer have a one-to-one correspondence with a projection angle, the look-up table will contain two or more projection angles for each wavelength (a one-to-many relationship). As a result, the multiple rainbow projection system requires an additional procedure to select the correct projection angle for a given wavelength.

[0040] Figures 8 and 9 is a graph and flowchart, respectively, outlining the procedure for conducting color matching for a one-to-many lookup table that contains multiple projection angles for a given wavelength. To avoid any mismatching from an incorrect

projection angle selection, the method shown in Figure 9 can be used to reduce any ambiguities.

[0041] First, adaptive control can be used to determine the initial condition in the search. More particularly, an adaptive initial point calculation mechanism may be used to ensure that the initial point at which the iterative search method begins is at least somewhat close to the correct result, particularly because the final result of iterative processes tends to depend on the selected initial condition. By limiting the search range, as shown in Figure 8, within one spectrum in the multiple-spectrum light pattern, the likelihood of a correct color match is greatly increased.

[0042] One method of increasing the chance for having a good initial point in a search is to use an adaptive initial point calculation mechanism. The initial point of the search is determined by a correct match point in the search of a neighboring pixel. The underlying assumption here is that most portions of the surface of a physical object being imaged are continuous. Thus the projected, i.e., reflected, color is similar for neighboring portions of the object, and therefore the initial projection angle value should also be very similar.

[0043] As can be seen in Figure 9, the process starts by determining origin point coordinates (x_0, y_0, z_0) at step 900. This point can be, for example, the upper right-hand pixel in the image. To compute the correct value for the desired point (x'_i, y'_i, z'_i) at step 902, the inventive system uses color matching to obtain projection angle candidates at step 904. For example, if the object is being illuminated with two identical rainbow spectra are arranged horizontally, i.e., right and left, with respect to each other, it can be assumed that the light resulting in the upper right-hand pixel of the image taken results from light in the right-hand spectrum as reflected by the object. Therefore, to identify the angle at which that light was originally emitted, θ, the wavelength of that light is matched to the angle at which that wavelength is being emitted in the right-hand, as opposed to the left-hand, rainbow spectrum. Once this angle is identified, the value for (x'_i, y'_i, z'_i) obtained at step 906 is compared with previously obtained neighborhood point $(x_{i-1}, y_{i-1}, z_{i-1})$ to determine the correct value for (x_i, y_i, z_i) at step 908. If the iteration process is determined to be complete at step 910, then the process ends. Otherwise, another iteration is conducted to refine the determination of the value of (x_i, y_i, z_i).

[0044] Note that although the look-up table for a multiple rainbow projection system has multiple projection angles associated with any given wavelength when the light pattern is viewed as a whole, the system restricts the search space in the color matching operation within a smaller range (e.g., within one sub-pattern) so that, as a practical matter, there is a one-to-one correspondence between the wavelength and the projection angle when the search is restricted to within the sub-pattern.

[0045] Referring to Figures 10a and 10b, the actual projection pattern appearing on the image received by the camera is the convolution of the projection pattern produced by the light source and the sensitivity characteristics of the image sensor. As shown in the Figure 10a, if an image sensor has a nonlinear sensitivity, a linear projection pattern provided by the light source may be distorted into a nonlinear variation pattern in the received image

[0046] To compensate for any nonlinear characteristics of the camera 102 or other image sensor used in the system, it may be desirable to pre-calibrate the characteristics of the image sensor 102, then apply its inverse function to the desired projection pattern design, resulting in a pre-distorted projection pattern, as shown in Figure 10b. The pre-distortion projection pattern compensates for any non-linearities in the camera or image sensor so that the final pattern on the image captured by the image sensor is ideal and distortion-free.

[0047] Although all of the above examples assume that there is only one camera or image sensor used to capture images of the illuminated object, multiple cameras can also be used to capture multiple rainbow projection pattern data. Referring to Figure 11, the light projector, marked ①, generates the multiple rainbow projection patterns, marked ②, to lighten the scene containing 3D objects of interest, marked ⑦. The reflected light is detected by a pair of color CCD cameras, marked ③ and ④. The images, which contain both intensity and color components, will be grabbed by a real time frame grabber board, marked ⑤, into a host computer, marked ⑥, to perform pixel-to-pixel color matching and triangulation calculation, based on the similarity of color patterns and intensity variation in the neighborhood of pixels in stereo image pairs.

[0048] The color spectrum of pixels on the captured images is determined by the proportion of Red, Green and Blue components (RGB) associated with the individual pixel. As a result, pixel-to-pixel registration can be easily performed based on matching the color components of counterparts. Because the length of the baseline B between the two cameras is known, and the geometrical and optical parameters of two cameras can be obtained from a prior calibration procedure, the locations of a pair of corresponding pixels in a stereo image pair provide sufficient information to determine viewing angles $\alpha 1$ and $\alpha 2$. The range values, R, associated with each pixel between a camera and surface points can be obtained using a straightforward triangulation:

$$R = B\frac{\sin(\alpha_2)}{\sin(\alpha_1 + \alpha_2)} \tag{11}$$

Thus, a full frame of a three-dimensional image can be obtained from a single snap shot, and a stream of three-dimensional images can be generated at the camera's frame rate (e.g., 30 frames per second or higher).

[0049] By using multiple cameras in conjunction with the multiple rainbow projection system, three-dimensional measurement accuracy is greatly improved, particularly when measuring objects and scenes that do not have many distinguishing surface features. More particularly, the stereo matching and triangulation methods used in this embodiment reduces the dependence of distinguishing features, such as edges and corners, on an object's surface in conducting the measurement.

[0050] Referring now to Figures 12a and 12b, the inventive system is not limited to systems using a color camera or color images, but can also be implemented using a monochromic camera and monochromic projection patterns. More particularly, a multiple rainbow projection pattern can be represented as a combination of three individual bands of color, namely red, green, and blue (or other colors, if a different color space is defined). Each band of color components (R, G, B) can be projected sequentially so that a monochromic camera can collect the reflected images for each color component upon each projection. These images are then combined to form a composite "color" image, which is equivalent to the color image produced by a color camera under the multiple rainbow projection, as illustrated in Figure 12a. Figure 12b outlines the method

corresponding to the sequential images illustrated in Figure 12a. The resulting composite image can be used like any color image and can be captured by systems employing one camera or multiple cameras.

[0051] Using a monochromic camera to obtain the color image generates high-resolution images using lower-cost, less complex equipment. However, because multiple images need to be obtained of any given scene to generate a full-frame three-dimensional image, this embodiment is most suitable for acquiring images of static or slowly moving objects.

[0052] Note that the above examples assumed that an optical filter is used to produce the illumination pattern, such as a rainbow pattern, on the object or scene being imaged. In this type of system the light from the light source is projected through the optical filter to generate the light pattern. The quality of the light pattern, however, depends greatly on the quality of the optical filter, which can be expensive and difficult to produce.

[0053] Figures 13 through 16a and 16b illustrate an alternative structure that can create multiple-periods of a light pattern having gradually changing intensities. Instead of using an optical filter, a planar member 1000 with slots 1002 cut through the member to form a slotted plate 1000, as shown in Figures 13 and 14, may be used. The slotted plate 1000 can be made of any non-transparent material and have any physical dimensions and any thickness. In a preferred embodiment, the width of each slot 1002 is made to be the same as the width of the material between the slots. Further, as illustrated in Figure 14, the cross-sectional shape of the slots themselves can have any desired shape and do not need to conform to any specific dimensions. The slotted plate 1002 can be placed in a similar position as the optical filter, in front of the light source so that the light from the source is projected toward the object being imaged through the slotted plate. As a result, a light projector using the slotted plate 1000 is able to generate the desired spatially-varying illumination pattern on objects in a scene with varying light intensity crossing the scene.

[0054] To generate the illumination pattern, assume that the illumination intensity on the surface of an object in a scene can be expressed as a function of the coordinate and the contribution of each point light source. The expression for the intensity then becomes:

$$Intensity = \int_s I(s,l)ds$$